UNITE DE RECHERCHE
INRIA-SOPHIA ANTIPOLIS

Rapports de Recherche

N° 1137

Programme 5
Automatique, Productique,
Traitement du Signal et des Données

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Novembre 1989

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ANALYSIS OF DYNAMIC CONFLICTS BY TECHNIQUES OF ARTIFICIAL INTELLIGENCE.

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ABSTRACT. Dynamic conflicts exhibit differential game characteristics and their analysis by any method which disregards this feature may be, by definition, futile. Unfortunately, realistic conflicts may have an intricate information structure and a complex hierarchy which don't fit in the classical differential game formulation. Moreover, in many cases even well formulated differential games are not solvable. In the recent years great progress has been made in Artifitial Intelligence techniques, put in evidence by successfull applications in Scientifique Modelling, Automated Engineering Design Processes as well as for Fuzzy and Intelligent Control Systems. This progress has raised hopes that Artifitial Intelligence methods can be of help also in solving complex dynamic conflicts. This scientific report outlines a feasible option which combines Artifitial Intelligence techniques with concepts of Differential Game Theory for attaining such an objective. A research effort in this direction has a great potential of success, but it requires a well planned and coordinated collaboration of qualified scientist in both disciplines.

ANALYSE DE CONFLITS DYNAMIQUES PAR DES TECHNIQUES D'INTELLIGENCE ARTIFICIELLE.

RÉSUMÉ. Toute tentative d'analyse des conflits dynamiques qui ignorerait leurs caractères de jeux dynamiques est par avance vouée à l'insignifiance. Malheureusement, la complexité des situations réalistes rend illusoire la recherche d'une solution mathématique complète, voire d'une formulation mathématique complète en termes de jeux différentiels. Aussi ce rapport analyse-t-il la possibilité de recourir à des techniques de système expert manipulant les concepts et solutions partielles issus de la théorie des jeux dynamiques.

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1. INTRODUCTION.

Activities of the human society have been always characterised by situations of conflict expressed in either political, economical or military terms. In all of these conflicts the decisions have been made by following some rational reasoning, called some times a "strategy". The search for optimal strategies in this sense has been an important objective of all decision makers. The need for some mathematical modelling of a conflict has been realized since the fifth century B.C., when the chineese general Sun Tzu had observed the correlation between victory in a battle and well calculated planning. In the last century a formal mathematical frame for conflict analysis was created [1]. It is the Theory of Games, a reckognized branch of Applied Mathematics, that provides the language and the concepts for describing and analysing strategies in a conflict characterized by several agents (players) with independent goals, each having only a partial control on the environment.

In most cases the conflict environment is not static. Its evolution in time can be described by some set of ordinary (or partial) differential equations or by their discretized equivalents. Such a mathematical model brings us to the domain of "dynamic" conflicts and to the theory of dynamic or Differential Games.

Anyone who wishes to carry out a meaningfull analysis of a real-life conflict is facing two major challenges:

1, to formulate a relevant and insightful mathematical model of the situation,

2, to solve a well posed mathematical problem based on the model.

However, these steps are only prerequisites for the *real solution*, which consists of interpreting the mathematical results in terms of the orginal conflict.

The main difficulty is imbedded in the attributes "relevant and insightful" of the modelling challange. If this task is not carried out properly it may be possible to solve the mathematical problem, but the formal results will be either irrelevant or even worse – misleading. The technical literature is full of intelectually intriguing mathematical game models, most of them being solved (or are at least solvable) by classical mathematical methods. Unfortunatly, there is virtually no evidence of a practical application of the mathematical results. As the models become more realistic the solution of the mathematical problem involved becomes more and more difficult, time consuming and expensive. This is the reason that in most cases decision makers prefere to rely on the alternative of "brut force" simulations using detailed pysical models with arbitrary or at the best, heuristically determined control strategies.

In the last decade great progress has been made in the domain of Artifitial Intelligence (AI). Both innovative concepts and efficient computation and search techniques were developped and put in evidence by successfull applications for Scientifique Modelling, Automated Engineering Design Processes as well as for Fuzzy and Intelligent Control Systems. This progress provides an indication that AI methods have the potential to be of help also in solving complex dynamic conflicts.

The objective of this scientific report is to outline a feasable option for the analysis of complex dynamic conflicts based on combining AI techniques with concepts of Differential Game Theory .

There seems to be a great potential of success for such an approach because the classical represantation of a dynamic conflict (essentially a multi-stage decision making process) by a "decision tree" is equivalent to a game in *extensive* form. The *pruning* of such a tree is one of the basic tasks of heuristic research techniques used in most AI programs. This observation indicates the compatibility of the two different scientific disciplines in the present context. A second aspect is related to the complementary and probably synergetic features of these disciplines. Differential games require an unambiguous and strict description of the problem to be solved and therefore complex *real-world* situations cannot be always introduced in such frame. In the contrary, AI is suitable for a qualitative, even fuzzy modelling, but cannot guarantee an optimal solution in the pure mathematical sense.

In the next section the difficulties of modelling and solving a realistic conflict as a differential game are discussed and illustrated by a simplified example of an air combat duel. In Section 3. the solution of a dynamic conflict by using only AI techniques is outlined as an alternative. The functional elements of an Expert System, designed for solving complex dynamic conflicts by combining AI techniques and Differential Game Theory concepts, are described in Section 4.

2. DIFFICULTIES IN A DIFFERENTIAL GAME SOLUTION.

The study of differential games as a model for dynamic military conflicts started durind the second world war. It emerged from the pioneering work of Rufus Isaacs on optimal pursuit and evasion attempting to model tactical air combat problems. Scientific investigation in this direction has continued since the early fifties without yielding (unfortunately) usefull applications. In the last decade there has been a renewed research interest in differential games. It is evidenced by three International Symposia on Differential Game Applications (1984 in Haifa, Israel; 1986 in Williamsburg, Virginia; 1988 in Sophia Antipolis, France) and by the great number of special sessions devoted to this topic in the last years at several international and national meetings of the automatic control community (IFAC, CDC, AIAA GN&C). There is a clear tendency of efforts to overcome the difficulties creating the gap between theory and applications.

The difficulties in solving a "well formulated" differential game have the following origin. The classical solution of a differential game [2] is based on simultaneous backwards integration of the state and adjoint equations, starting at the target set (terminal manifold) of the game, in order to fill the entire game space by the ensemble of optimal trajectories. The backwards integration is a rather direct operation as long as no singular surface of the game, implying a discuontinuity of the adjoint vector, is encountered. Experience has shown that there are several different singular surfaces which are frequently encountered in differential game solutions. The game solution requires, once a singular surface is reached, to determine the type of singularity and to continue the backwards integration accordingly.

As the first step, the existence of the singular surface has to be identified by observing the intersection of *retrograde* trajectories belonging to different end conditions. In a simple game, with no more than two state variables, such intersection can be easily visualized. For a differential game of three independent state variables the same process becomes very combersome and for dynamic models of higher dimension it is virtually impossible.

At the other end, the numerical solution of a "two-point boundary-value problem" associated with the differential game satisfies only the necessary conditions of optimality. Though this method can be applied to dynamic models of any order (at the cost of increasing computational effort), it cannot identify the singular surfaces of the game and has no tool to verify the sufficiency conditions of the game solution. For this reason the usefullness of this method is rather limited.

One can also encounter great conceptual difficulties in the attempt to formulate a dynamic conflict as a differential game. This can be well illustrated by an example of an air-to-air combat duel between two fighter aircraft carrying guided missiles. A simple pursuit-evasion game formulation is certainly not suitable for such a scenario. Rather, the conflict has to be viewed as an interaction of a "two-target differential game" (between the aircraft) with two independent missile-aircraft "pursuit-evasion games". The target sets in the two-target game are the respective missile firing zones, each being the "capture zone" of a missile-aircaft pursuit-evasion game of kind. The encounter between the two aircraft (say Blue and Red) exhibits a "threat reciprocity" and must terminate with one of the following outcomes:

a., Red alone is shot down = Blue wins

b., Blue alone is shot down = Red wins

c., Both are shot down = Mutual kill

d., Both survive = Draw

The solution of the two-target differential game with the given target sets is a qualitative one, namely the decomposition of the set of admissible initial conditions into the respective zones of fixed outcome. Inside of the Blue and Red winning zones many zero-sum pursuit-evasion games of degree can be played with the winning player (the pursuer) minimizing and its opponent (the evader) maximizing the same cost function. Different cost functions may yield different optimal strategies, but all games have the same guaranteed outcome, namely the termination of the game (in some finite time) on the terget set of the winning player. If the engagement starts in the "mutual kill" zone both players have to be aggressive, otherwise the state of the game may slip to the opponent's winning zone. However, cooperative strategies can drive the state of the game to the "draw" zone. In the "draw" zone each player can guarantee his own survival against any action of the opponent, but cooperative aggressive strategies can lead to a "mutual kill".

A version of this air combat duel was recently analysed as a game of kind by a simplified dynamic model of the "game of two cars". In this game model the target sets represented the "capture zones" of advanced all-aspect, "fire and forget" air-to-air missiles [3]. This modelling assumption implies that game termination on one of the target sets is equivalent to a missile firing which garantees the destruction of the opponent, even if it employs an optimal missile avoidance strategy. Curiously, the interpretation of the apparently satisfactory results obtained in this investigation raised the problem of a conceptual incompleteness of the two-target game formulation, as explained briefly in the the sequel.

Inside the winning zone of Blue, contrarely to the classical assumption, Red (the loser) may have no interest to behave defensively by playing the role of an evader. Though he cannot force the game to his own target set (the "capture set" of his missile), he can still fire a missile within the classical firing envelope assuming a straight flying oppenent. Such a firing disrupts the original two-target game by starting an unexpected pursuit-evasion game between the Red missile and Blue aircraft. In order to survive, Blue must take an evasive action. This action will lead to a successfull escape from the missile, but may prevent him – at least temporarely – from reaching an effective firing opportunity, i.e., the victory guaranteed by the two-target game solution. Moreover, during this evasive maneuver Red may be able to escape from the Blue winning zone.

The insight gained by this interpretation presents a warning, which indicates that the frame of classical Differential Game Theory is rather limited to accomodate even relatively simple models of a "real-world" dynamic conflict.

Another difficulty is related to the very nature of the solution concept. In future air combat most engagements will start at rather long (beyond visual) ranges, thus the initial conditions of the aboved described two-target game are generally in the "draw" zone. Therefore the only guaranteed outcome of such non-cooperative game is a "draw". This result, which denies the very essence of an air-to-air combat, – and consequently the justification of the high cost of advanced aircraft and missile development, – is clearly unacceptable from an operational point of view. At the other end, cooperative strategies are also inadmissible in a hostile environment. The inherent non-cooperative nature of the scenario requires from each player to determine his "preference ordering" between a "mutual kill" and a "draw" and to act accordingly. Such "preference ordering" is one of the elements of the players' strategy and therefore not known by the opponent. This uncertainty implies a major difficulty in the proper mathematical formulation and consequently in a meaningful analysis of the dynamic conflict exhibited in an air-to-air combat duel.

If one of the players prefers a "draw" and plays the corresponding optimal strategy, the opponent cannot enforce his prefered outcome. For initial conditions in the "draw" zone an eventual victory of anyone of the players is not possible, unless the other player fails to act acording to his optimal defensive strategy. Such a situation, which arrives frequently in real-life conflicts, can be exploited by the opponent by using an appropriate *reprisal* strategy.

Moreover, one has to remember that future air combat will be fought by groups of adversary fighter aircraft and not by individual pilots. An air-to-air combat duel is, therefore, only the simplest example and eventually a building block of the more complex multiple scenarios. Successfull solution of the air-to-air combat duel is certainly a prerequisite, but it is only an element of the complete conflict.

The points raised in this section jointly indicate that Differential Game Theory alone cannot provide a satisfactory solution to complex dynamic conflicts, such as a realistic air-to-air combat.

3. AN ALTERNATIVE SOLUTION BY ARTIFICIAL INTELLIGENCE.

As a consequence of the difficulties outlined in the previous section, one is strongly tempted to search an alternative approach for the analysis of dynamic conflicts. A priori, Artifitial Intelligence seems to to represent such an alternative. The example of a "chess-playing" computer program demonstrates the feasibility of the idea.

Every dynamic conflict is essentially a multi-stage decision making process and can be represented as such by a "tree". Such representation is indeed identical to a game in its *extensive* form [4]. In fact, a differential game is also a game in *extensive* form and equivalent to a "decision tree" of infinite nodes. By discretizing time a finite "game tree" is obtained. The nodes of the tree represent the state of the game, where the players can select their controls for a given period of time. The branches of the tree are the moves in the game space. The *pruning* of such a tree is one of the basic tasks of heuristic search techniques used in most AI programs. In the case where the players don't change their decision at every node (selected by arbitray discretization of the time scale), some moves can be aggragated to a single branch and the resulting "game tree" becomes simplified. It is also possible that the players don't make their decisions simultaneously and in this case Blue and Red moves can be distinguished. Such an approach was pursued recently with some succes [5].

Using AI techniques for the analysis of dynamic conflicts allows a qualitative description of the problem, which is extremely important in complex situations. Another favourable feature of AI is related to the already mentioned heuristic search techniques, which provide a way of solving problems for which no more direct approach is available. In such a search process any other available computational technique can be easily embedded. AI techniques can facilitate the solution of complex problems, such as conflicts, by exploiting the knowledge on the structure of the objects involved. Moreover,by using *abstraction* AI provides a way of separating important features and variations from the many unimportant ones, that otherwise may overhelm the entire solution process.

There is no formal guarantee that an AI program will find the "true" optimal solution of a complex dynamic conflict. There are, however, two positive AI features that compensate for this defficiency: interaction with a human operator and "learning". Most AI programs are structured to allow a human operator to interact with them by asking questions, providing missing inputs or even by modifying goals and constraints. There are AI programs that can improve their performance by changing their own structure as the consequence of previous operations.

In order to possess all the above mentioned favourable features AI programs are in general complex softwares. They require, in addition to the problem oriented *knowledge base*, a great amount of knowledge for own managment. Moreover, the very selection of an efficient method for solving the problem may require a considerable amount of specific knowledge on the problem domain. This is the reason that, though all Expert Systems provide some general structure for knowledge representation and an inference engine to manipulate it, a system designed for a give problem domain cannot be used or even modified for other purposes. In other words, "expertise" includes the knowledge of the the particular concepts and methods for obtaining the solution in a particular problem domain.

In order to obtain an efficient solution of complex dynamic conflicts, it seems to be necessary to include concepts of differential games in the *knowledge base* of an AI program designed for this purpose. Analysis of such conflicts by using only "classical" heuristic search methods may turn out to be not only combersome, but also unaccurate and unsatisfactory.

4. AN EXPERT SYSTEM FOR SOLVING DYNAMIC CONFLICTS.

In this section the elements of an Expert System, designed to solve complex dynamic conflicts, and its functioning are outlined. In this system AI techniques and Differential Game Theory concepts are combined. The basic idea is to incorporate in the *knowledge base* of the system the elements of "expertise" necessary to solve diferential games. The characterisation of the respective elements will be as general as possible. However, as an illustrative example of a dynamic conflict the already mentioned air-to-air combat with missiles will be used.

Realistic dynamic conflicts, such as an air combat, are characterized by the following features:

a, the moves in the *real* conflict are irreversible,

b, the conflict is composed of several interacting elements,

c, the conflict environment is only partially predictable,

d, the optimal solution is not always obvious,

e, there is a need, in general, to interact with a human operator.

These features suggest that the Expert System of interest should have a set of particular properties. First, it must solve the problem by an *off-line* "planning" mechanism before the user is committed to any *real* action (a,). The solution can be based on eventual decomposition of the original conflict to well defined subproblems (b,). When the "planning" process is completed and the plan is accepted by the decision maker, the first actions can be taken. However, since the environment and the behavior of the opponents are not fully predictable (c,) it has to be verified *on line* that the original plane is still valid. Such a *real-time* "monitor" serves as a mechanism which either authorizes the execution of the plan, or activates a new "planning" process.

A very important funcional element of the Expert System is an *intelligent* "interface" with the decision maker (e,). It is a human being who in most conflicts must make the critical decisions. It is him who has to accept the proposed plan and its predicted outcome as satisfactory, because the optimal solution is not always obvious (d,). Moreover the conflict environment may change in a way that unpredictable readjustments of the system are required. Such an action can be performed only by a human being directly involved in the conflict.

Both the *real-time* "monitor" and the *intelligent* "interface" are, in spite of the their great importance, only supporting elements of the *off-line* "planning" mechanism which has to resolve actually the dynamic conflict. An approach for obtaining the solution of a complex dynamic conflict by the combination of AI techniques and Differential Game Theory concepts is outlined in the sequel.

By using this approach the very solution of a complex dynamic conflict starts, as already mentioned, by a decomposition of the conflict to a set of well defined and numerically solvable *subgames*. This most critical phase requires deep knowledge in the problem domain, as well as formal knowledge of differential game concepts. A subgame can be considered numerically solvable if its solution is either known, or it can be simulated by approximating the respective optimal strategies.

There are in fact several types of solvable subgames. The first distinction is between complete subgames, which represent a possible way of playing the entire conflict, and secondary subgames describing only a phase of the conflict. A complete subgame is generally composed by a sequence of secondary subgames. These definitions provide a direct analogy to the classical "tree" structure. The branches of the "tree" are the respective secondary subgames and the nodes are the transitions between such subgames.

Another distinction is between optimal subgames, which guarantee a predictable outcome in the *saddle point* sense, and *reprisal* subgames based on exploiting an assumed non optimal adversary behavior. This distinction is very important, because strategies based on an optimal game solution are *security* strategies, while using a *reprisal* strategy always involves a *risk*. A complete subgame is an "independent" subgame if it is not interacting with any another complete subgame. Two "independent" subgames are, by definition, mutually exclusive options of playing the conflict.

The above given definitions can be illustrated by some air combat examples. An air-to-air combat duel is composed of a set of consecutive missile firing sequences. Each missile firing sequence can be decomposed into three phases: a *pre-launch* phase, a *post-launch* phase and an eventual *avoidance* of the adversary missile. Each phase can be considered as a well defined and numerically solvable optimal secondary subgame. If each aircaft has only one missile to launch than a firing sequence of each aircraft, composed of the above defined three phases, is a complete subgame. The transition from one phase to the following one depends on the pilot's decision when to launch his missile and when to start the *aviodance* maneuver from the missile launched by the opponent. Consquently, there are many possible firing sequence scenarios. The firing sequence subgame of an aircraft is not an "independent" subgame, because it interacts with the firing sequence of the adversary. The union of two adversary firing sequences becomes a more complex, but "independent" complete subgame. These examples show the hierarchical structure of the decomposed conflict.

The solution of the air-to-air duel conflict for each pilot consists of finding the "optimal timing" for own missile launch and for initiating the *avoidance* from the adversary missile. This problem doesn't have a known solution. It is the role of the "planning" mechanism of the Expert System to provide the respective pilot with an optimal, or at least satisfactory, proposition for the two critical decisions. This task may require a rather extensive search in the parameterized space of the pilot strategies. The search can be simplified by using some (or several) rational behavior model of the opponent. In this case the respective subgames are *reprisal* subgames. The heuristic search for the satisfactory solution (as defined by the pilot) can be made a very efficient one by exploiting knowledge on air combat and on differential games.

This "planning" approach with a probabilistic adversary behavior model was implemented recently [6] using a simplified dynamic model of an air-to-air combat duel. In this study the optimal strategies of the secondary subgames are known and a complete firing sequence subgame can be directly simulated for any given pilot decision on the timing of missile launch and the *avoidance* phase. The *knowledge base* of the Expert System includes the definition of differential game concepts, as well as a simulation module for *reprisal* subgame solution. The inference engine manipulates the subgame simulations and drives an rule based automated reasoning process to guide the search. In a prototype design, suitable for an exploratory study with a simplified model, only a relatively small set of rules were implemented. Nevertheless, the tools were prepared for a larger and consequently more complex system that will be required both for a realistic multipled aircraft scenario, where the number of rules and the complexity of rule interaction may increase by orders of magnitude. Moreover, the prototype design allowed to demonstrate the feasibility and the usefullness of incorporating differential game concepts in the *knowledge base* of an Expert System for solving a dynamic conflict.

5. CONCLUSIONS.

In this scientific report a feasible option is outlined for the analysis of complex dynamic conflicts. This option is based on incorporating in the *knowledge base* of an Expert System the basic definitions and solution concepts of Differential Game Theory. Such an approach benefits of the compatibility and the complementary features of both disciplines: Artifitial Intelligence and Differential Game Theory. Some recent university investigations [5, 6] demonstrated the feasibility of such an approach ,as well as its effectiveness in the analysis of yet unsolved complex dynamic conflicts such as an air-to-air combat. Though air combat is a particularely interesting example, the proposed approach is equally suitable to analyse other complex dynamic conflicts.

As everyone knows, there is a great distance between a feasibility demonstration of any new idea and its *real world* application. The challange to develop a full scale Expert System which can be used in realistic dynamic conflicts is tremendeous indeed. It will certainly need a large amount of work expressed in terms of several men-years. But more importantly, it requires a carefully outlined development plan with coordinated colaboration of qualified scientists of both disciplines involved in the effort.

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Imprimé en France
par
l'Institut National de Recherche en Informatique et en Automatique